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Special Report 85-10

July 1985

US Army Corps of Engineers

Cold Regions Research & Engineering Laboratory

Acoustic waves incident on a seawater/sea ice interface

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Prepared for
OFFICE OF NAVAL RESEARCH

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SECURITY CLASSIFICATION OF THIS PAGE *(When Data Entered)*

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER Special Report 85-10	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* ACOUSTIC WAVES INCIDENT ON A SEAWATER/SEA ICE INTERFACE		5. TYPE OF REPORT & PERIOD COVERED 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Kenneth C. Jezek		8. CONTRACT OR GRANT NUMBER(s) N0001485WRM2407
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army Cold Regions Research and Engineering Laboratory Hanover, New Hampshire 03755-1290		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Arlington, Virginia 22217		12. REPORT DATE July 1985 13. NUMBER OF PAGES 10
14. MONITORING AGENCY NAME & ADDRESS *(if different from Controlling Office)*		15. SECURITY CLASS. *(of this report)* Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT *(of this Report)*

Approved for public release; distribution is unlimited.

17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*

18. SUPPLEMENTARY NOTES

19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)*

Acoustic signals
Arctic Ocean
Seawater/sea ice interface
Underwater sound signals

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

Simple plane wave theory is used to compute the energies of reflected and transmitted elastic waves at a seawater/sea ice interface. The results indicate that for incident angles between 30° and 60°, most of the scattered energy is in the form of transmitted shear waves for typical values of sea ice and seawater densities and elastic wave velocities.

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PREFACE

This report was written by Dr. Kenneth C. Jezek, Geophysicist, Geophysical Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding was provided by the Office of Naval Research under contract number N0001485WRM2407.

The author thanks Stephen F. Ackley and Dr. Anthony J. Gow, both of CRREL, for technically reviewing this manuscript.

ACOUSTIC WAVES INCIDENT ON A SEAWATER/SEA ICE INTERFACE

by

Kenneth C. Jezek

INTRODUCTION

Acoustic signals propagated in the Arctic Ocean can scatter at the ocean bottom and at the sea ice canopy. Crary (1954) studied the problem of compressional (P) and distortional (shear or S) waves incident on a sea ice/seawater interface in conjunction with seismic studies on an Arctic ice island. More recently, several investigators have completed straightforward analyses of the reflectance of acoustic waves at a perfectly smooth seawater/sea ice interface because understanding sound propagation in the Arctic Ocean is important to underwater surveillance and detection schemes (Mayer 1974, Mayer et al. 1975). In this paper, I extend the results of the earlier work to examine both the reflected and transmitted waves at a seawater/sea ice interface. This work is motivated by acoustic experiments in the sea ice test facility at CRREL where the back-scattered echo strength from the underside of sea ice and transmission through the sea ice in the forward direction are being measured.

THEORY

The theory for computing the amplitude of reflected and refracted plane waves at a perfectly smooth boundary between a liquid and a solid is well known (Knott 1899). The solution starts by defining two potentials, ϕ and ψ, that are related to the compressional and distortional wave motions. Then, wave equations in ϕ and ψ are solved under appropriate boundary conditions to yield ratios of the incident and scattered wave potentials.

The application of this approach to a slab of sea ice overlying a semi-infinite ocean basin is limited by several assumptions. First, multiple reflections in the slab are ignored by postulating that the incident energy is a short pulse for which the material properties are non-dispersive. (This limitation can be relaxed if interference between the multiply scattered waves is important.) Second, Poisson's constant (σ) is taken to be equal to 0.25. This minimizes the algebra involved in computing the reflection and

transmission coefficients without seriously distorting the results. (Poisson's constant $\sigma = 0.25$ implies that the compressional wave velocity is equal to the cube root of three times the shear wave velocity. Roethlisberger [1972] has tabulated values of the elastic wave velocities in sea ice that show this assumption is approximately true.) Third, plane wave theory does not accurately predict the amplitude of lateral waves and, in this analysis, I ignore Rayleigh waves and flexural waves. Therefore, the predicted amplitudes are likely to be most in error near critical angles (Press and Ewing 1951, Oliver et al. 1954, Mayer et al. 1975). Fourth, bulk material properties are taken as appropriate to the entire slab of sea ice. This assumption is especially weak near the ice/water interface where there is the highest density of channels filled with liquid brine. However, Mayer's (1974) reanalysis of Langleben's (1970) data on the reflectivity of sea ice suggests that ice near the ice/water boundary can support shear waves. So, I suspect the analysis in this paper to be valid as long as the wavelengths are much greater than the dimensions of brine drainage channels and the individual crystals in which the channels are aligned.

Solution of the wave equations subject to the above restrictions yields three ratios for the reflected and refracted P-wave and refracted S-wave potential.

$$\frac{\phi_r}{\phi_i} = \frac{\rho' r\left[\left(\frac{c^2}{\beta^2} - 2\right)^2 + 4r's\right] - \rho\, r'\frac{c^4}{\beta^4}}{\rho' r\left[\left(\frac{c^2}{\beta^2} - 2\right)^2 + 4r's\right] + \rho\, r'\frac{c^4}{\beta^4}}$$

$$\frac{\phi_T}{\phi_i} = \frac{2\rho\left(\frac{c^2}{\beta^2} - 2\right)\frac{c^2}{\beta^2}\, r}{\rho' r\left[\left(\frac{c^2}{\beta^2} - 2\right)^2 + 4r's\right] + \rho\, r'\frac{c^4}{\beta^4}}$$

$$\frac{\psi_T}{\phi_i} = \frac{-4\rho\,\frac{c^2}{\beta^2}\, r r'}{\rho' r\left[\left(\frac{c^2}{\beta^2} - 2\right)^2 + 4r's\right] + \rho\, r'\frac{c^4}{\beta^4}}$$

where ρ is the density of seawater, ρ' is the density of sea ice, β is the shear wave velocity in sea ice and c is the horizontal phase velocity. (c becomes infinite at normal incidence.) The remaining variables are defined by

$$r = \cot\,\theta_p = \sqrt{\frac{c^2}{\alpha^2} - 1}$$

$$r' = \cot\,\theta'_p = \sqrt{\frac{c^2}{\alpha'^2} - 1}$$

$$s = \cot\,\theta_s = \sqrt{\frac{c^2}{\beta^2} - 1}$$

where θ_p, θ_p' and θ_s are the deflection angles of the reflected P-wave, the refracted P-wave and the refracted S-wave, α is the compressional wave velocity in sea water and α' is the compressional wave velocity in sea ice (Ewing et al. 1957). Note that these angles become imaginary if the critical angle is exceeded. These ratios can be used to evaluate wave energies through the equations

$$\frac{E_r}{E_i} = \frac{\phi_r^2}{\phi_i^2}$$

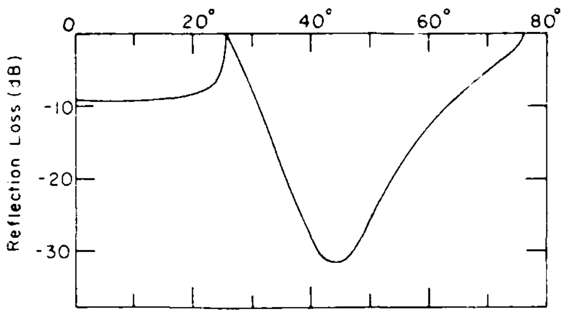
$$\frac{E_T}{E_i} = \frac{\rho'}{\rho}\,\frac{r'}{r}\,\frac{\phi_T^2}{\phi_i^2}$$

$$\frac{E_s}{E_i} = \frac{\rho'}{\rho}\,\frac{s}{r}\,\frac{\psi^2}{\phi^2}$$

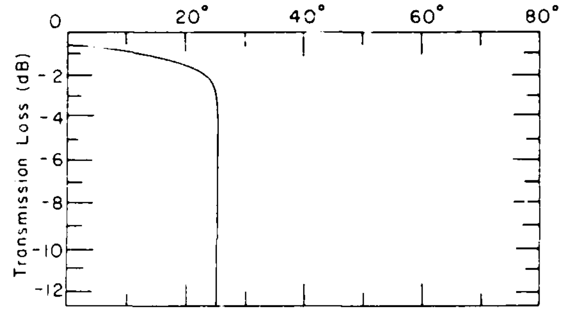
where E_r is the energy of the reflected P-wave, E_T is the energy of the transmitted P-wave, E_s is the energy of the transmitted shear wave and E_i is the energy of the incident wave.

ANALYSIS AND DISCUSSION

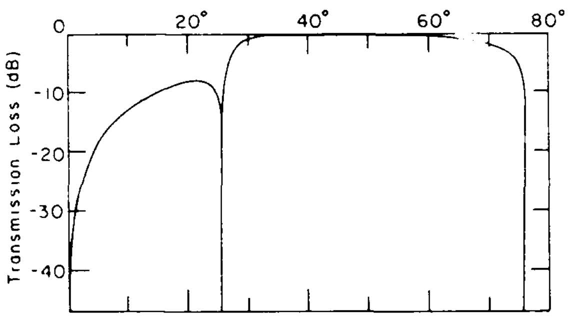
I used two sets of velocities and densities to compute reflected and transmitted energies. In the first case (Fig. 1) I took the "standard" values quoted by Mayer et al. (1975). Specifically, $\rho' = 0.917$ g/cm^3, $\rho = 1.03$ g/cm^3, $\alpha = 1500$ m/s, $\alpha' = 3500$ m/s and $\beta = 1550$ m/s. The second set of material constants (Fig. 2) corresponds to values I believe appropriate to the conditions in the CRREL sea ice test facility. These are: $\rho' = 0.91$ g/cm^3; $\rho = 1.03$ g/cm^3; $\alpha = 1450$ m/s; $\alpha' = 3500$ m/s; $\beta = 1550$ m/s. (The wave speed in water was measured by carefully timing signals reflected off the bottom of the sea ice and detected by a receiver at a known depth. The density of the sea ice was estimated by determining the volume and weight of



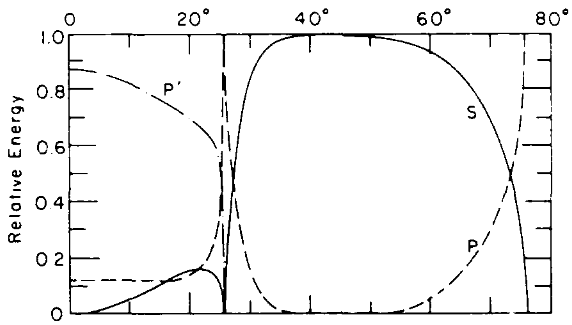
a. Reflected P-wave.



b. Transmitted P-wave.



c. Transmitted S-wave.



d. Relative energy, curves for the reflected compressional (P), transmitted compressional (P') and transmitted shear (S) waves are shown.

Figure 1. Reflection and transmission coefficients, standard values of material properties ($\rho' = 0.917$ g/cm^3, $\rho = 1.03$ g/cm^3, $\alpha = 1500$ m/s, $\alpha' = 3500$ m/s and $\beta = 1550$ m/s).

slabs removed from the sea ice sheet.* The compressional wave velocity was crudely estimated on the basis of the strength of normally reflected acoustic waves from the base of the sea ice.) Mayer et al. (1975) give a more complete discussion of the change in reflection coefficient with changing material properties.

The results (Fig. 1 and 2) are presented in terms of the ratios of the scattered to incident waves expressed in dB. Also presented are curves of the relative energy of each wave. Phase information is suppressed in this presentation.

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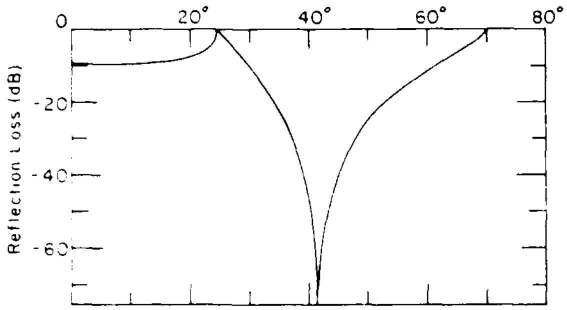
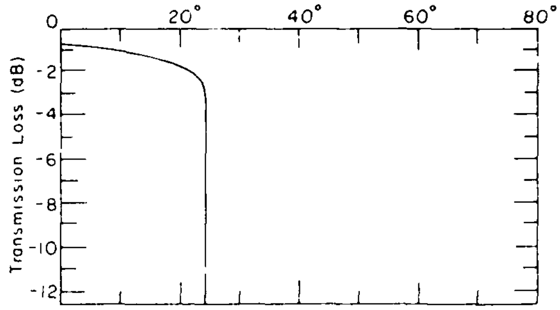
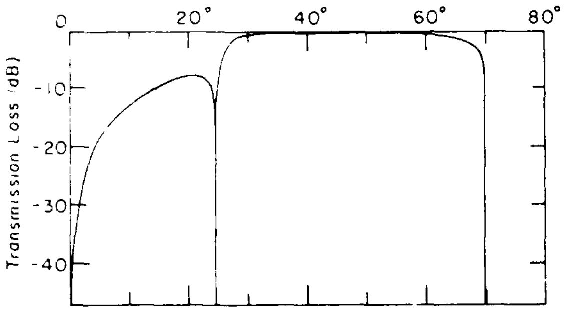
* Personal communication with S. Arcone, CRREL, 1984.



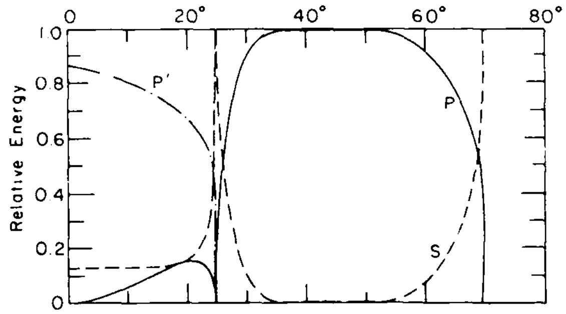
a. Reflected P-wave.



b. Transmitted P-wave.



c. Transmitted S-wave.



d. Relative energy.

Figure 2. Reflection and transmission coefficients, test facility properties ($\rho' = 0.91\ g/cm^3$, $\rho = 1.03\ g/cm^3$, $\alpha = 1450$ m/s, $\alpha' = 3500$ m/s and $\beta = 1550$ m/s).

The results for the two cases that I considered show transmitted P-wave cutoff angles at about 25° and S-wave cutoff angles at about 70°. Reflected P-wave amplitudes are nearly constant to within a few degrees of the cutoff angle. For incident angles between 30° and 60°, the reflected P-wave is severely attenuated. S-wave amplitudes increase in this region and there is nearly complete transformation of the incident acoustic energy into shear wave energy in the sea ice.

The observation that a significant partition of energy from incident acoustic waves to transmitted shear waves occurs at incident angles between 30° and 60° suggests that mode conversion is an important factor when considering sound propagation beneath the Arctic sea ice cover. This also suggests that sensors placed on the surface of the sea ice to detect underwater sound will be more likely to detect P-waves at incident angles less than 30° and more likely to detect S-waves at angles between 30° and 60°.

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